Fermi National Accelerator Laboratory

Measurement of ε'/ε at Fermilab[*]

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The current status of the measurement of "direct" CP violation parameters ε'/ε in the Fermilab experiment E731 is reviewed. Preliminary results on upper limit for the decays $K_L \to \pi^0 e^+ e^-$ and $\pi^0 \to e^+ e^-$ (from 20% of the data taken in 1987-88) are also reported.

CP-violation was discovered[1] more than twenty years ago, but so far has only manifested itself in the neutral kaon system. The superweak model was suggested[2] as the *origin* of such small CP-violation, which only occurs in the mixing of the mass matrix of K^0 and $\bar{K}^0$ ($\Delta S = 2$). However, the 6-quark KM model in the standard electroweak theory predicts[3] that CP-violation exists not only in the mass matrix, but also in the decay amplitude ($\Delta S = 1$), so called "direct" CP-violation. Experiment E731 at Fermilab was designed to study the direct CP-violation parameters ε'/ε in the 2π decay mode of K_L and K_S, where

$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon', \qquad \eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

and

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} = \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 = 1 + 6\left|\frac{\varepsilon'}{\varepsilon}\right|.$$

The standard KM model predicts that ε'/ε lies in the range of 1 to 7×10^{-3}, whereas the superweak model predicts zero. To measure ε'/ε with accuracy better than 10^{-3}, we need to measure the double ratio of 2π decay rates $\Delta R/R$ less than 6×10^{-3}. This requires very *good statistics*, especially for the CP violating decays $K_L \to 2\pi$, and a *good control of systematics*, which includes

1. Imperfect knowledge of the K_L and K_S beam fluxes and their momentum spectrum, and of reconstruction efficiencies.
2. Time dependent losses due to trigger inefficiencies, accidental vetos, resolution changes and electronics drifts.
3. Background subtractions for decays of $K_L \to 3\pi^0$, $K_L \to \pi e\nu$, $\pi\mu\nu$, and for neutron interactions and non-coherent K_S.
4. Acceptance differences for K_L and K_S decays.
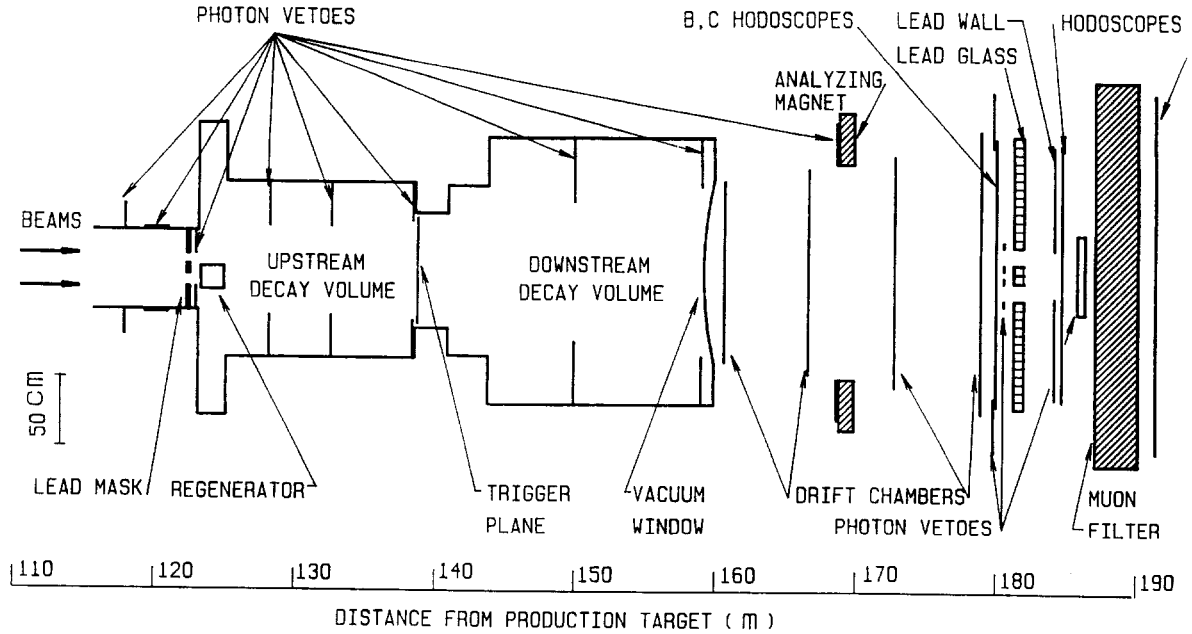5. Stabilities of energy scale and energy resolution in the detector.

FIG. 1. Schematic of E731 detector, elevation view.

The apparatus is shown in Fig.1. The experiment detected both K_L and K_S decays *simultaneously* with the same detector by bringing double K_L beams 120 m from target on a boron carbide regenerator alternating between the two beams every machine cycle to produce K_S beam. 4 layers of scintillators were interleaved in the regenerator to reduce inelastic and diffractive regeneration events. The K_L or K_S then decays in the 14 m vacuum decay region downstream of the regenerator. This gave us very good control of the systematics, since the experiment had nearly identical momentum spectra and *cancellations* of beam flux, dead time, inefficiencies and accidental losses.

For the charged mode ($K_{L,S} \rightarrow \pi^+\pi^-$), 4 sets of drift chambers and an analyzing magnet were used to measure the 4-momenta of the pions. Each chamber consisted of 2 horizontal and 2 vertical planes, and had a position resolution of 130 μm. For the neutral mode, $2\pi^0$ decays were measured by a lead-glass calorimeter consisting of 804 blocks (5.8x5.8 cm^2 and 20 radiation lengths each) stacked in a circular shape with two holes in the middle for the beams to pass through. It had a position resolution of 3 mm and energy resolution of $\sigma/E = 2\% + 6\%/\sqrt{E}$ for photon detection from π^0 decays. Wide angle photon veto counters were placed at various apertures, as shown in Fig. 1, including vetos in front and behind beam holes of the lead-glass array to suppress copious $3\pi^0$ decays. e^+e^- calibration data were taken regularly once every 2 to 3 weeks. Data from a xenon light flasher system feeding all 804 blocks, were used to monitor gain shifts throughout the entire running period. Figure 2 shows the E/P distribution from one calibration run; an average resolution of 3.1% was obtained, where E is the electron energy from the lead-glass array and P is the momentum measured by the spectrometer.
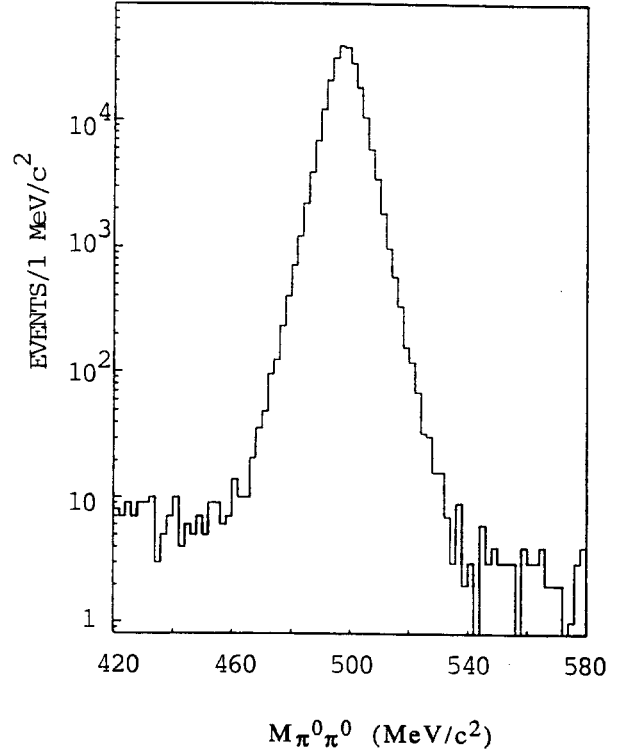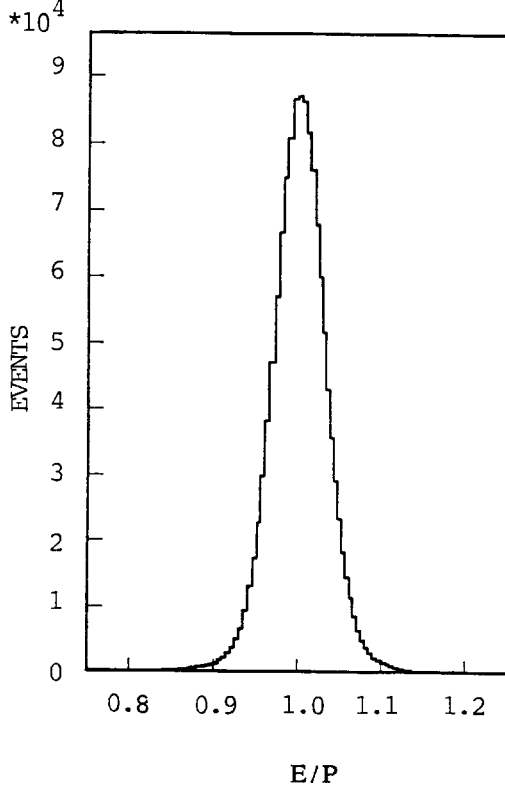
FIG. 2. E/P for calibration electrons.   FIG. 3. Reconstructed $\pi^0\pi^0$ mass for K_S.

The $2\pi^0$ events are reconstructed using a "π^0 pairing" algorithm, namely any two photons reconstructed could be used to calculate a z-vertex:

$$z^2 = E_1 E_2 \frac{r^2}{m_{\pi^0}^2} \ .$$

Here E_1, E_2 are energies of the photons and r is the distance between the center of two photon clusters in the lead-glass array. In the case of $2\pi^0$ (4 photons) final states, there are 3 different pairing combinations. One then finds the best case of vertex matching via the lowest chi-square quantity. Figure 3 shows the reconstructed $2\pi^0$ mass distribution of regenerated events. A clear K_S peak of a mass resolution of 4.5 MeV/c^2 is seen with little background.

The experiment had a test run in 1985 and just completed its main data run (July 87' - February 88'). During 1985 test run we collected $K_{L,S} \rightarrow \pi^0\pi^0$ events in conversion mode, which requires one of the photons converted into an e^+e^- pair at the end of decay region by a 0.1 radiation length lead-sheet converter. The final statistics of this test run are summarized in Table I. The result of the ratio of CP-violating parameters $|\varepsilon'/\varepsilon|$ has been published elsewhere:[7]

$$\left|\frac{\varepsilon'}{\varepsilon}\right| = +0.0032 \pm 0.0028(\text{stat.}) \pm 0.0012(\text{syst.})$$

Table I. Final data sample from 1985 test run

Decay mode	Events	Background (%)	Systematic error (%)
$K_L \to \pi^0\pi^0$	6,747	1.56	0.31
$K_S \to \pi^0\pi^0$	21,788	2.94	0.16
$K_L \to \pi^+\pi^-$	35,838	1.23	0.18
$K_S \to \pi^+\pi^-$	130,025	0.31	0.04

A significant increase in statistics was achieved in the 1987-88 run. Several modifications were made to improve the yield and to reduce the systematics and background. A hardware "cluster finder" was used to trigger on 4-cluster events, eliminating the need to require a photon conversion at the end of the decay region. This increased our neutral mode yield by a factor of 6. We also upgraded the readout system, which reduced the readout deadtime by nearly a factor of 2. Other improvements included, reducing the diffractive K_S background, a much improved photon veto system and better lead-glass calibration. We collected about 300K $K_L \to \pi^0\pi^0$ and 400K $K_L \to \pi^+\pi^-$ with approximately 3 times more in each of the corresponding K_S decays. This gives a statistical precision for $|\varepsilon'/\varepsilon|$ of better than 0.0005. We would also push our systematic uncertainty down to this level. About 20% of the data were taken with all 4 modes together (prescaling charged mode events), which should *minimize* some possible systematics due to time dependent or beam intensity related biases. Preliminary results based on this 20% data sample will be presented here.

Figure 4 shows the reconstructed $2\pi^0$ mass distribution of K_L events with a semilog scale. The $3\pi^0$ background has been reduced to 0.3% (a factor of 5 better than 1985 run) from the improvements in the photon veto system and offline rejection of photon fusion events. Figure 5 shows the reconstructed center of energy $2\pi^0$ event distribution verses no. of equal-area box rings from the center of the K_S beam. The non-coherent K_S backgrounds are currently under study, but can be estimated to be about 3% for K_S (in Fig. 5) and about 5% for K_L. There are about 226K K_S and 66K K_L to $2\pi^0$ events in the mass region 484 to 512 MeV/c². Figure 6a and 6b show the reconstructed $\pi^+\pi^-$ mass distributions of K_S and K_L decays with a mass resolution of 3.4 MeV/c², and with Monte Carlo events superimposed. There are about 224K K_S and 71K K_L to $\pi^+\pi^-$ events in the mass region 484 to 512 MeV/c². The low-mass tail came mainly from radiative $\pi\pi\gamma$ decays (see below). Figure 7a and 7b show the p_t^2 distribution for K_S and K_L to $\pi^+\pi^-$ with a background fit superimposed. The inelastic and diffractive background for K_S has been reduced (about a factor of 2) to 0.14% with $p_t^2 < 250$ MeV²/c². The background from semileptonic decays in $K_L \to \pi^+\pi^-$ is 0.37% (a factor of 3 lower than the 1985 run) with the same p_t^2 cut as K_S.

One other potential background is the CP-allowed $K_L \to \pi\pi\gamma$ (direct emission) decays in the charged mode. Figure 8a and 8b show the gamma energy

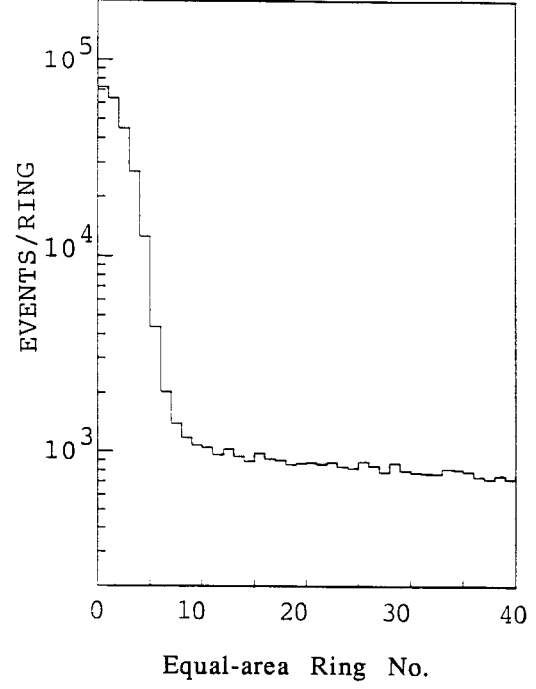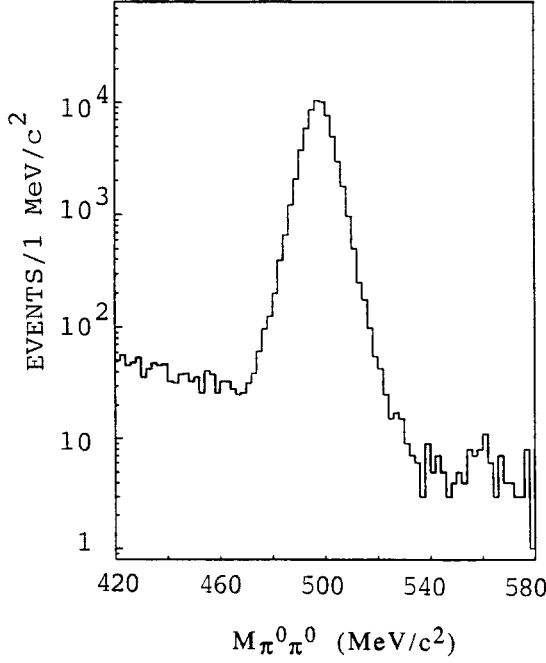FIG. 4. Reconstructed $\pi^0\pi^0$ mass of K_L.

FIG. 5. Noncoherent background of $K_S \to \pi^0\pi^0$.
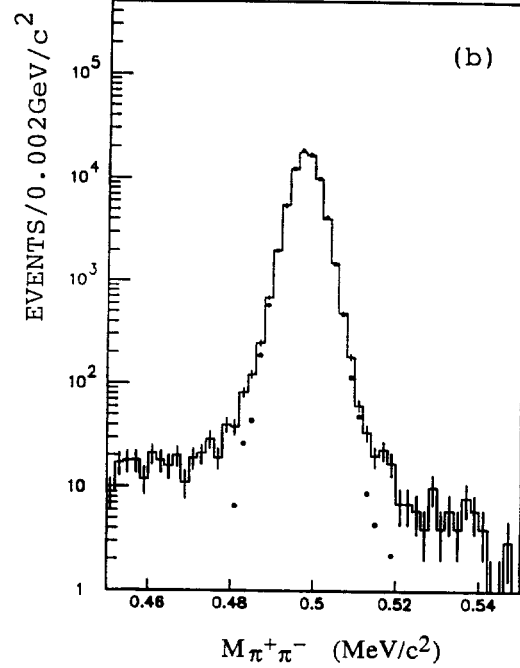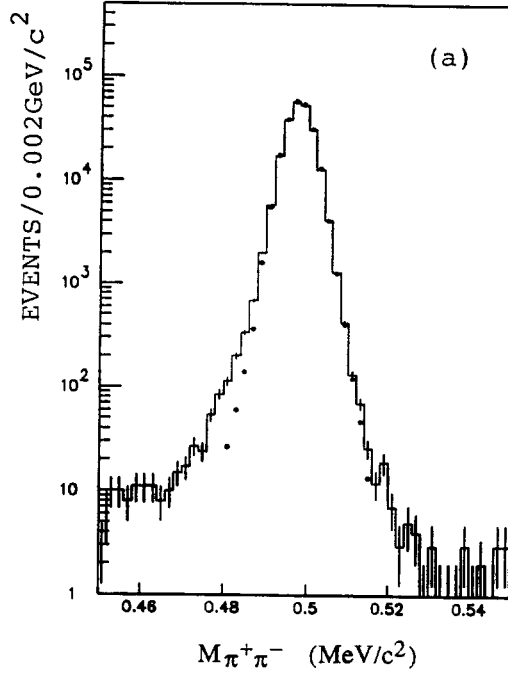

FIG. 6. Reconstructed $\pi^+\pi^-$ mass distribution for (a) K_S, (b) K_L decays, where solid line is data and black circle is Monte Carlo simulation.

(E_γ^*) distributions in the center of mass system of the identified $\pi\pi\gamma$ events for K_S and K_L respectively. The $K_S \to \pi^+\pi^-\gamma$ has the $1/E_\gamma^*$ inner bremstrahlung distribution, but $K_L \to \pi^+\pi^-\gamma$ has both inner bremstrahlung and direct
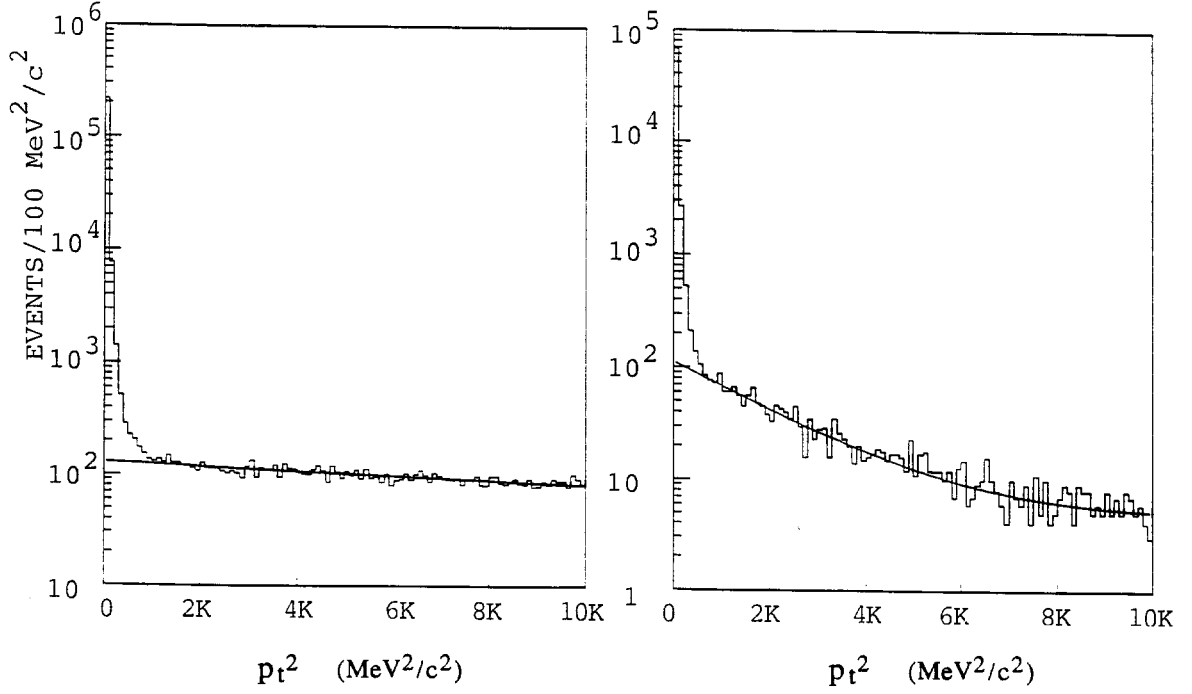
FIG. 7. Reconstructed p_t^2 distribution for (a) $K_S \to \pi^+\pi^-$, (b) $K_L \to \pi^+\pi^-$ events with background fit superimposted.
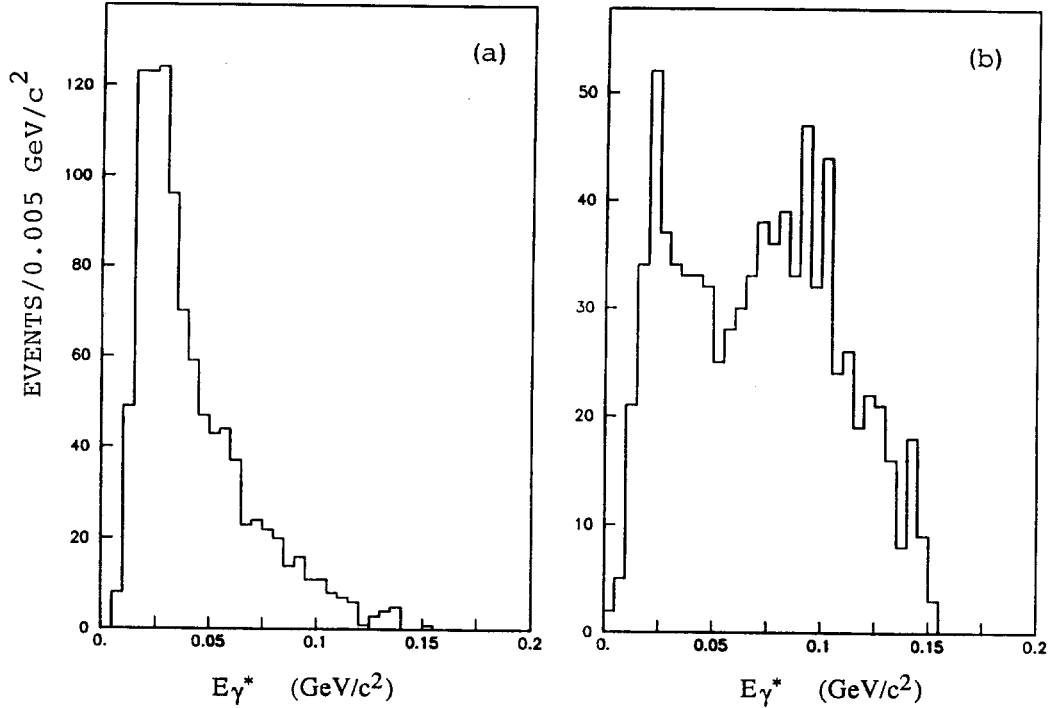

FIG. 8. Gamma energy distribution in c.m.s. of $\pi^+\pi^-\gamma$ events for (a) K_S and (b) K_L decays, note that K_L has the direct emission component.

emission ($\propto E_\gamma^{*3}$) components.[5] If one could not correct for such events, the direct emission background would contribute a systematic error on $|\varepsilon'/\varepsilon|$ of

2.4×10^{-3}. Fortunately with good mass and p_t^2 resolution, the direct emission background has negligible contribution ($\approx5\times10^{-6}$) to $|\varepsilon'/\varepsilon|$.

We now turn to the subject of rare decay searches based on 20% of the data. From the "4-cluster" triggers in neutral mode, one can look for the rare decays $K_L \to \pi^0 e^+ e^-$ for the observation of CP violation in a decay amplitude. The CP violating amplitude via the one photon exchange penguin diagram is expected to be comparable or larger than the conserving one.[6] Theoretical estimates of the branching ratio are in the 10^{-11} range, while the current limit is $<2.3\times10^{-6}$. The $e^{\pm}$ was identified by matching the track with the cluster, and requiring $0.85 < E/P < 1.15$. The π^0 mass resolution was determined to be 4 MeV/c^2 from $K_L \to \pi^+\pi^-\pi^0$ decays. The $\gamma\gamma$ mass was then required to be within 10 MeV/c^2 of the nominal π^0 mass. By constraining the $\gamma\gamma$ mass to the nominal value, the reconstructed kaon mass ($M_{\pi ee}$) would have a resolution of 4.5 MeV/c^2 and the p_t^2 of the $\pi^0 e^+ e^-$ would have a resolution of 50 MeV^2/c^2. The candidates are displayed in Fig. 9b. The signal region is defined to be $p_t^2 <$ 200 MeV^2/c^2 and $489 < m_K < 507$ MeV/c^2; a Monte Carlo study found that these cuts would include about 95% of the signal. No candidates were found in the signal region. Figure 9a shows the equivalent region for $K_L \to \pi^+\pi^-\pi^0$ decays. This gives the results[7] B.R.($K_L \to \pi^0 e^+ e^-$) $< 4.2\times10^{-8}$ and B.R.($K_S \to \pi^0 e^+ e^-$) $< 4.5\times10^{-5}$ (90% C.L.). This is the first upper limit for the K_S decay, and 50 times better than the previous limit for the K_L decay.
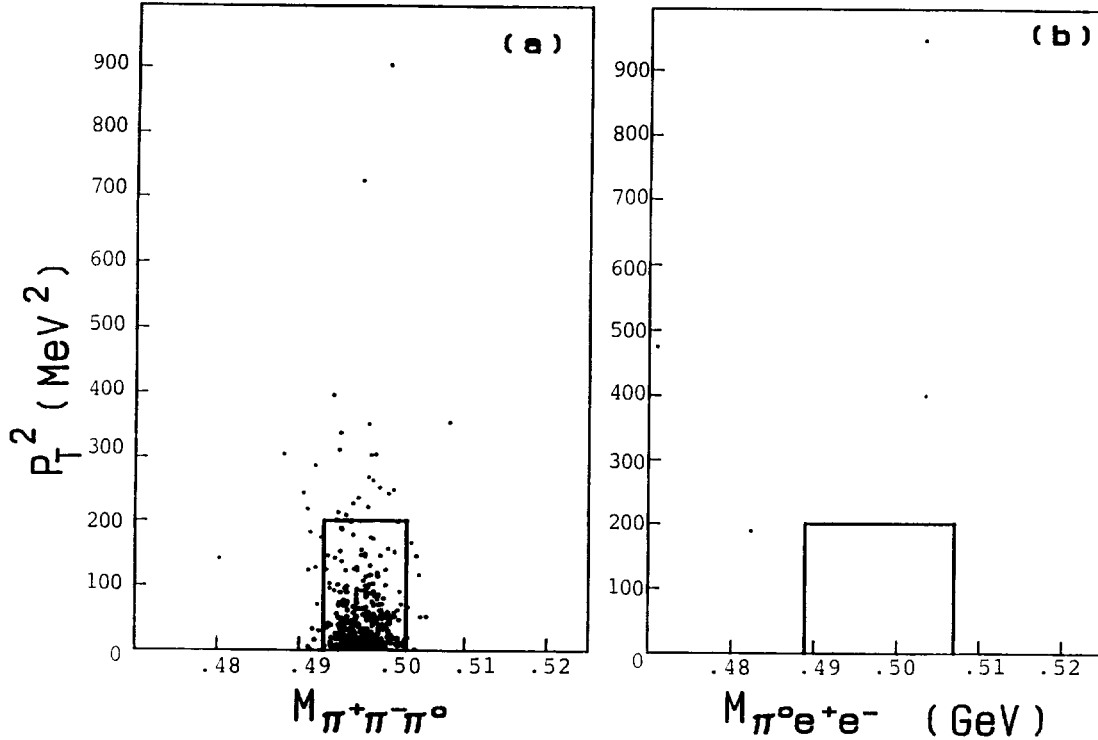

FIG. 9. Reconstructed kaon mass vs p_t^2 for (a) $K_L \to \pi^+\pi^-\pi^0$, (b) $K_L \to \pi^0 e^+ e^-$.

A search for $\pi^0 \to e^+e^-$ was performed using tagged π^0 from $K_L \to 3\pi^0$, where one π^0 decays to e^+e^- and other two π^0's decay into 4 photons. The mass of the final state $\pi^0\pi^0e^+e^-$ was constrained to 478 to 518 MeV/c^2 (2.5σ) and the $p_t^2 < 200$ MeV^2/c^2; we also required the e^+e^- mass within 127 to 143 MeV/c^2 (2.5σ) and the two $\gamma\gamma$ masses each within 10 MeV/c^2 of the nominal π^0 mass. No events were observed in the signal region. This gives the preliminary result B.R.($\pi^0 \to e^+e^-$) < 2.5×10^{-7} (90% C.L.); more data will be analyzed later to improve this limit. The previous experimental result[8] was $(1.8 \pm 0.7) \times 10^{-7}$, but the theoretical calculation[9] prefers a value around 5×10^{-8}.

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DISCUSSIONS

Q What is the ultimate sensitivity expected for $K_L \to \pi^0 e^+e^-$ from your experiment? (D. Bryman)
A: We should be able to reach $< 10^{-8}$ with 4 times more data in hand.

Q What is likely to be your sensitivity for detecting $\pi^0 \to e^+e^-$? (N. W. Tanner)
A: We can reach 10^{-7} with all the $K_L \to 3\pi^0$ data that we have taken.

Q You quoted an estimate on the systematic error of the new experiment of 5×10^{-4} on ε'/ε. What are the three largest contributions to this estimated error? (K. Kleinknecht)
A: The largest one probably came from non-coherent K_S background subtractions in the $K_{L,S} \to \pi^0\pi^0$ which we are currently working on. The rest systematic uncertainties (e.g. energy calibration, acceptance and other background subtractions) will have roughly the same contributions.